Radiative Transfer in Spiral Galaxies: Dust Extinction and Emission

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Abstract. I review the results of our Monte Carlo models for the radiative transfer in the dusty disks of spiral galaxies. The simulations are compared to observations of dust extinction in the optical and emission in the FIR, with the aim of deriving the amount of interstellar grains, their distribution and the internal extinction in a galaxy. I discuss the main, puzzling, result of this comparison: more dust is needed to explain thermal emission than what is inferred from extinction studies.

RADIATIVE TRANSFER IN SPIRAL GALAXIES

Dust has an enormous importance in shaping the SED of a spiral galaxy. By absorbing radiation in the UV-Optical-NIR, dust grains may prevent the exact determination of the intrinsic properties of the stellar distributions, like e.g. luminosity, color, morphology and star formation rate (SFR). On the other hand, dust re-emit the energy absorbed from starlight in the MIR and FIR. Thus, an analysis of the SED in those spectral ranges not only allows the study of the dust properties but could also be used to retrieve the information the grains have concealed from the stellar radiation.

However, the effects of dust on the SED cannot easily (and/or correctly) interpreted without solving the radiative transfer equation for the dusty medium in a galaxy. The solution is made difficult by the presence of a scattering term in the equation, which cannot be neglected a priori for starlight: in the UV-Optical-NIR, a good fraction of the light impinging on a dust grain is scattered ($\sim 50\%$). Furthermore, it is necessary to consider geometries appropriate to a spiral galaxy's stellar and dust distribution, as simplistic assumptions may produce misleading results [1].

Only a few method are available to solve the full radiative transfer equation in arbitrary geometries [1]. Among them, the Monte Carlo method is conceptually simple and probably the easiest to implement. I review here the work we have done on radiative transfer in spiral galaxies using the Monte Carlo method.

THE MODEL OF EXTINCTION

In [2] we have described the stellar disk of a spiral galaxy with a double exponential,

$$\rho = \rho_0 \exp\left(-\frac{r}{\alpha_\star} - \frac{|z|}{\beta_\star}\right),$$

where $\alpha_\star$ and $\beta_\star$ are the radial and vertical scalelengths of the distribution. Observations in the Milky Way and in other spirals suggest $\alpha_\star/\beta_\star \approx 10-15$ [3] with trends of smaller $\beta_\star$'s [4] and larger $\alpha_\star$'s [5] for bluer starlight (although the radial color gradients can also be explained with extinction [6]). For analogy, the same distribution is adopted for the dust disk, with independent scalelengths α_d and β_d. Commonly, it is assumed that $\alpha_d = \alpha_\star$ and $\beta_d \approx 0.5\beta_\star$. The first assumption is chosen because of its plausibility, while the second is dictated by the need of reproducing the extinction lanes observed in edge-on galaxies; Fig. 1). I refer to this as the *standard model*. A spheroidal distribution of stars can be added to the stellar and dust disks to simulate the bulge in late type spirals.

The amount of dust in the disk is usually defined by assigning the V-band optical depth through the center of a face-on disk, τ_V. The opacity at a different wavelength λ is then scaled adopting an extinction law (τ_λ/τ_V). Two other dust properties are needed for the radiative transfer: the albedo, ω_λ, which tells us how much of the radiation intercepted by a dust grain is scattered along a direction different from the original path of the light beam; and the scattering phase function, Φ_λ, describing the fraction of diffused radiation as a function of the angle between the old and new light path. For these properties we have used either models [7] or observations [8] of Milky Way dust.

Solving the radiative transfer problem with the Monte Carlo method consists in following the *random walk* of photons inside the dust distribution. At each step of the walk, the fate of a photon is determined in a probabilistic way by tossing random numbers. The position where the photon is emitted is drawn from the adopted stellar distributions, while the initial direction is derived assuming isotropy. Along a given path of optical depth τ, the probability for a photon to avoid extinction (the cumulative effect of absorption and scattering) is $e^{-\tau}$; using this probability, we can draw the optical depth along the path at which the photon encounters a grain. If such optical depth is larger than the total optical depth along the photon traveling direction, the photon escape the dust distribution and can be recorded by an *observer*. It it is smaller, the photon suffers either scattering (the probability is equal to ω_λ) or absorption (the probability of such event is 1-ω_λ). If the photon is scattered, the phase function Φ_λ is used to draw the new traveling direction. The process is then repeated on the new path, until the photon exit. Several cycles are needed to produce high S/N results (integrated photometry or maps as in Fig. 1). This basic scheme can be optimized to reduce the computational time (i.e. number of cycles) necessary to achieve a certain S/N) [9, 10].

In [2] and [12] we have described the behavior of several observable quantities (e.g. total magnitudes, surface brightnesses, color gradients) as a function of the inclination and opacity of the disk. Obviously more inclined models suffer more extinction, as light traveling along the plane of the dust disk has a larger probability of being either absorbed or scattered off the plane: optically thin ($\tau_V < 1$) face-on models of standard disks show pronounced extinction lanes when seen edge-on (Fig. 1). For the same reason, the effects of scattering are larger for disks seen face-on. The amount of extinguished radiation increases with τ_V but, eventually reach a saturation when stars high above the plane of the galaxy (outside the dust distribution) become the dominant component of the galactic flux. This is particularly evident in models with bright bulges [13]. The same effect prevents the color of a galaxy to become indefinitely redder for increasing τ_V. Clearly the behavior of the complex stellar/dust geometry is different from that inferred from observation of Galactic stars obscured by a foreground dust screen. This

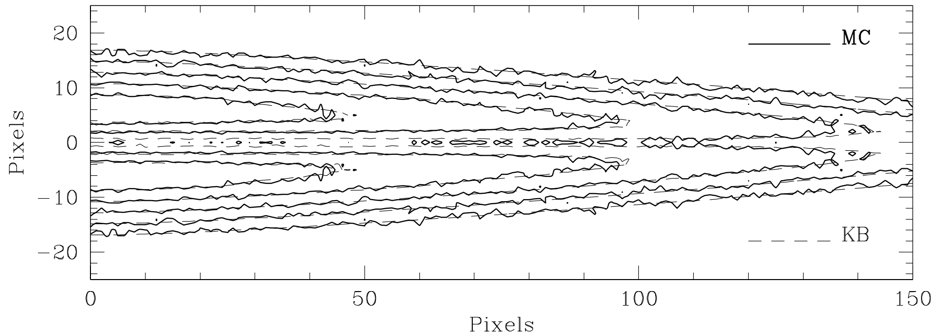

FIGURE 1. Monte Carlo radiative transfer model of a $\tau_V = 1$ edge-on *standard disk* (solid line contours). The dashed contours refer to the solution obtained with the method of Kylafis & Bahcall [11, 1].

is particularly true when studying the wavelength dependence of the ratio between the light which comes out of each simulated image and the light which would come out in transparent models. A screen of dust would show the same features present in the adopted extinction law (e.g. the 2175Å bump for Milky Way dust). In galaxy models, instead, the observed flux includes light coming from different regions and having suffered different absorption and scattering. This makes the λ dependence of the *attenuation law* smoother than that of the intrinsic extinction law adopted for the dust. However, radiative transfer effects in a standard smooth model are not able to cancel completely big features like the 2175Å bump. Thus, the featureless *Calzetti law* [14] derived on starburst galaxies implies a different dust composition or size distribution in those objects.

THE MODEL OF EMISSION

In [15] we have extended the radiative transfer study to the emission of dust heated by the diffuse interstellar radiation field (ISRF). Emission models were then compared to FIR data to constrain further the parameters describing the dust distribution.

In the Monte Carlo procedure I have described previously, the position where photons are absorbed can be easily stored, together with the amount of absorbed energy. Once a stellar/dust geometry and a SED are chosen, several monochromatic simulations are run at different wavelengths, to cover the whole spectral range of stellar emission. The final product is a map of the energy absorbed by the grains in the dust disk.

The map of absorbed energy needs then to be converted into a map of temperature. Since we were interested mainly in emission at $\lambda > 100\mu$m, we considered thermal emission only. However, part of the stellar radiation is also absorbed by small grains, which are subject to stochastic temperature fluctuations. The resulting emission is mainly in the MIR regime at $\lambda < 60\mu$m and constitutes about 20-30% of the total infrared dust output. Using a dust model [16], we have subtracted the energy that goes into this non equilibrium emission from the map of absorbed energy derived with the Monte Carlo. Then, the dust temperature at thermal equilibrium was computed using emission properties for diffuse dust in the Milky Way. The adopted emission efficiency, or emissivity,

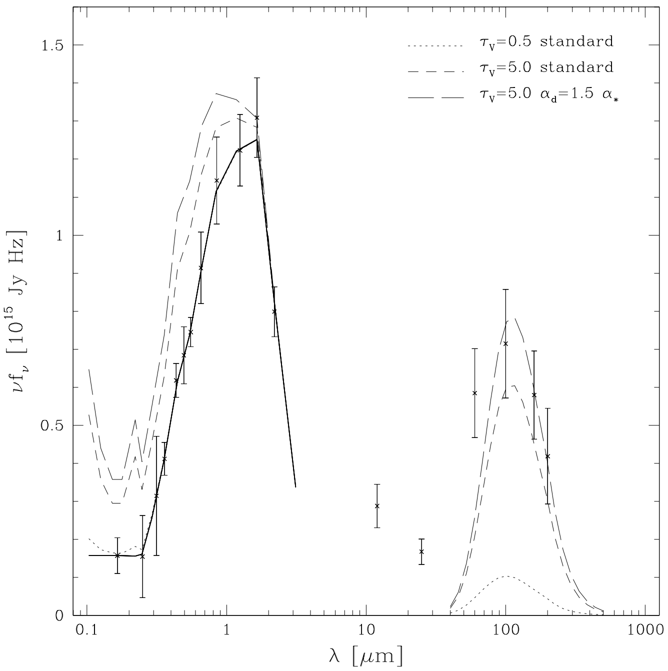

FIGURE 2. Observations and models of the SED of NGC 6946 [15]. The solid line is the stellar SED derived from the observations (data points), which is the common UV-optical-NIR output for all models. The intrinsic, dust-free, stellar SED (shown for each single model in the figure) is derived from the radiative transfer simulations. The SED of dust emission is shown for each model in the FIR.

was obtained from FIR observations of the cirrus component in our Galaxy [17]. As FIR emission can be reasonably assumed to be optically thin (and this was the case for the model we explored), a map of dust emission can be easily obtained by integrating the emission coefficient (a modified blackbody) along the chosen line of sight.

Simulations were produced for the nearly face-on spiral galaxy NGC 6946. This galaxy was chosen both because its stellar SED was well covered by observations from the UV to the NIR, and because of relatively good coverage of the FIR dust emission (Fig. 2). For each adopted geometry and τ_V, we carried out radiative transfer calculations in 17 bands in the UV-optical-NIR. For each λ, the simulations were normalized to produce the same output in radiation as observed. Thus, we derived the intrinsic, dust-free, emission that would result in the observed, dust-extinguished, flux. As a result, the intrinsic dust-free stellar SED depends on the adopted geometry and τ_V. In NGC 6946, $\approx$30% of the galaxy bolometric luminosity is emitted by dust in the infrared. In this, NGC 6946 is very similar to other late type spirals in the nearby universe [18]. Therefore, the dust distribution must be able to absorb 30% of the stellar radiation. Usually, this comparison between stellar and dust energy outputs is called *energy balance*.

I show in Fig. 2 the SED obtained for an optically thin (τ_V=0.5) and thick (τ_V=5) standard ($\alpha_d/\alpha_\star$=1.0) models. All models have smooth exponential stellar and dust distributions with $\beta_d/\beta_\star$=0.5 and it is assumed that the relative stellar/dust geometry does not change with the wavelength of the starlight. The temperature distributions are very similar for all the models we have explored, with gradients and values compatible with those derived in the Milky Way for cold dust (T≈20K). Thus, the position for the peak of dust emission does not change significantly with the model. The maximum, instead, varies a lot with τ_V (Fig. 2). An optically thin standard model does not absorb enough stellar radiation (only 5%) to match the observed emission. Only if $5 < \tau_V < 10$ the dust distribution can match the observed SED, with 25-40% of the total bolometric luminosity absorbed from starlight and re-radiated in the FIR.

The results do not change significantly if $\beta_\star$ is allowed to decrease with λ (younger stars having thinner disks [4]) or if a bulge is included. Both cases have a slightly larger efficiency in absorbing starlight for the same τ_V because more stellar emission is inside the dust distribution [19]. However, the difference is not enough. Thus, we concluded that it is not possible to produce the necessary FIR output with optically thin models, at least when the stellar and dust components are described with smooth distributions and when the properties for diffuse Milky Way dust are used.

DISCUSSION

Other works based on the energy balance between stellar and dust emission agree with the need for $\tau_V > 1$ [20, 21, 22]. This result is in contradiction with what usually obtained, using a variety of methods, for the diffuse dust component in a spiral galaxy [14]. Indeed, low values of τ_V are generally found, implying that dust disks are almost transparent, when seen face-on, and unable to produce significant internal extinction and obscuration of the distant universe in their background [23].

In particular the results from the energy balance are opposite to what found by direct comparisons between radiative transfer models for smooth dusty disks and observations of edge-on galaxies in the optical/NIR. Xilouris et al. [24, 25], using the Kylafis & Bahcall [11, 1] approach, fitted the surface brightness distribution of seven galaxies and obtained the parameters for the dust (disk) and stellar (disk + bulge) components. They derived a mean central face-on optical depth for the sample, $< \tau_V > \approx 0.6$, with opacities in different bands essentially following the Milky Way extinction law. Models that fit observations have $< \beta_d/\beta_\star > \approx 0.5$ (necessary to explain the dark extinction lane) and $< \alpha_d/\alpha_\star > \approx 1.4$ (the dust disk being more extended than the stellar disk).

Since a dust disk more extended than stars absorbs more radiation that a standard disk of the same τ_V, we repeated our simulation for this dust/star geometry. An extended model fits reasonably well the observed data if τ_V=5 (Fig. 2), with 30% of starlight absorbed (of which 70% emitted at thermal equilibrium). A disk with the mean opacity of the fitted models, instead, does not have the necessary FIR energy output.

Popescu et al. [26, 27] and Misiriotis et al. [28] modeled the dust emission for 5 of the 7 galaxies analyses by Xilouris et al. [24]. First, they noted that the fitted distributions alone cannot reproduce the dust emission (they include stochastic heating as well). Thus, they added to the stellar distributions an UV emitting disk, thinner than the fitted dust distribution (i.e. $\beta_\star^{UV}/\beta_d < 1$). Part of the UV radiation is assumed to suffer localized absorption and to emerge in the MIR-FIR with the typical spectrum of HII clouds. The total UV luminosity is scaled with the SFR, so that the model can fit the emission in the two IRAS bands at 60μm and 100μm. The SFR values needed for this are consistent with what normally observed in spirals. However, even with this refinement, the model is not able to fit the emission at longer wavelengths, as they found out on the two galaxies for which they had datapoints in the submm/mm. A further dust disk is needed for that, increasing the dust mass in the galaxy by a factor between 2 and 4. The new dust disk is required to be as thin as the UV disk, for its extinction effects to be undetectable in the thicker extinction lane produced by the optically thin dust disk.

Thus, even the more sophisticated model of Popescu et al. [26] needs more dust to reproduce emission than what is found by comparing radiative transfer models with optical/NIR observations of edge-ons. A possible way of hiding dust from extinction (and to make it count more in emission) is to distribute part of it in clouds. The extra dust disk can thus be a simple description for a complex clumpy structure, not easily represented in a radiative transfer simulation. Alternatively, the discrepancy between extinction and emission models can be imputed to the uncertainty in the FIR/submm emission properties of dust. In the following, I comment on these two issues.

Clumping

Smooth dust (and stellar) distributions are only a first approximation in the description of galactic disks, which are observed to have a complex clumpy structure. In [29] and [30] we have studied the radiative transfer through a clumpy disk, using the Monte Carlo method. The three dimensional space was divided in cells and each of them was assigned a smooth or clumpy status. For the smooth component we have adopted a standard exponential disk of dust. The clumpy dust medium was assumed to be associated with the molecular gas component of a spiral disk. We allowed for different fractions of the dust mass to be locked in clumps (25, 50 and 75%), analogous to the fraction of gas mass in the molecular component in late-type galaxies; the properties of the clumps (mass, size of the cell) were derived from those of giant molecular clouds: as a result, we have optically thick ($\tau_V \approx 4$) clumps with a ring or exponential distribution, inferred from observations of molecular gas in the Milky Way and in late type spirals.

As expected, models in which the distribution of dust is clumpy have a higher transparency than models in which the same amount of dust is in a smooth disk. However, for the parameter range we have explored the effects of clumping are moderate, with changes in attenuation laws and in the amount of absorbed energy of less than 30% in the V-band. When examining edge-on images, we noticed that the surface brightness profiles for simulations with clumping are brighter than those for smooth models of the same dust mass, but they are similar in shape. Thus, they could be interpreted as if light were attenuated by a more transparent dust disk. As a consequence, fitting real images with radiative transfer simulations in smooth models may lead to an underestimation in the disk opacity. To test this, we have used the Monte Carlo simulation to produce mock images of edge-ons including clumping and we have fitted them with the technique of Xilouris et al. [24]. We found that the dust mass could be underestimated by $<$40%, if clumping is not taken into account. Therefore, clumping can partially explain the discrepancy between the energy balance results and the studies of extinction.

Unfortunately, the results depend heavily on the adopted parameters. In the models of Kuchinski et al. [31] most of the dust mass is in the clumpy phase and edge-on simulations are not much different from those obtained with smooth distributions. In this case, the neglect of clumping would not have consequences on the fits of edge-on galaxies.

So far, I have only discussed clumping for the dust distribution. If we allow for the stellar distribution to be clumpy as well, with a fraction of the starlight to be emitted inside clouds (as it is the case for young stars), a model with clumping could be less transparent than a smooth one, depending on the amount of embedded radiation [29]. This is particularly important in model of emission, since dust heated by localized sources can reach higher temperature (and emission) than dust heated by the diffuse ISRF. This has not been explored yet in radiative transfer models of spiral galaxies.

Emissivity

If one believes that there is no more dust than what is derived from the fits of edge-on galaxies, then the submm/mm emission can be reproduced by raising the dust emissivity. This explanation was preferred by Alton et al. [32], by using the same data and model for the galaxy NGC 891 from which Popescu et al. [26] inferred the presence of an extra dust disk. Successive analysis on a larger sample [33, 25] have confirmed that, for the dust disk seen in extinction to produce the observed submm emission, the dust emissivity must be ≈ 4 times higher than what predicted by models of dust grains [7] and derived from observation of diffuse emission in the Milky Way [34, 17] and other galaxies [35].

Such high values for the emissivity are instead found for dust associated with denser clouds in the Milky Way, like e.g. in dark cores [36, 37]. The larger emissivity is due to grain coagulation and growth of ice mantels in those dense environments [38]. The need for high submm emissivity in galaxies is puzzling, since it seems to imply that the emission from cold dust is mostly produced by grains in molecular clouds. This is also at odds with the smooth distributions assumed in the radiative transfer model, which are chosen to model the diffuse extinction produced by dust. However, it has to be considered that the value of the emissivity for diffuse dust in the Milky Way is still quite uncertain [33].

To conclude, the last decade has seen a considerable improvement in the study of the radiative transfer inside dusty galactic disks. The increasing amount of data, in particular the observations of nearby objects which are starting to come from the instruments aboard GALEX and SPITZER, will allow a detailed understanding of the SED and morphology of emission in spiral galaxies, thus solving the open issues I have described here.

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REFERENCES

1. Kylafis, N. D. 2004, in *The Spectral Energy Distribution of Gas-Rich Galaxies: Confronting Models with Data*, Heidelberg, 4-8 Oct. 2004, eds. C.C. Popescu and R.J. Tuffs, AIP Conf. Ser., in press
2. Bianchi, S., Ferrara, A., and Giovanardi, C., *ApJ*, **465**, 127 (1996).
3. de Grijs, R., and van der Kruit, P., *A&AS*, **117**, 19 (1996).
4. Mihalas, D., and Binney, J., *Galactic astronomy: Structure and kinematics*, W. H. Freeman and Co., San Francisco, 1981.
5. de Jong, R., *A&A*, **313**, 377 (1996).
6. Peletier, R., Valentijn, E., Moorwood, A., Freudling, W., Knapen, J., and Beckman, J., *A&A*, **300**, L1 (1995).
7. Draine, B. T., and Lee, H. M., *ApJ*, **285**, 89 (1984).
8. Gordon, K. D., Calzetti, D., and Witt, A. N., *ApJ*, **487**, 625 (1997).
9. Gordon, K. D., Misselt, K. A., Witt, A. N., and Clayton, G. C., *ApJ*, **551**, 269 (2001).
10. Baes, M. et al., *MNRAS*, **343**, 1081 (2003).
11. Kylafis, N. D., and Bahcall, J. N., *ApJ*, **317**, 637 (1987).
12. Ferrara, A., Bianchi, S., Cimatti, A., and Giovanardi, C., *ApJS*, **123**, 437 (1999).
13. Tuffs, R. J., Popescu, C. C., Völk, H. J., Kylafis, N. D., and Dopita, M. A., *A&A*, **419**, 821 (2004).
14. Calzetti, D., *PASP*, **113**, 1449 (2001).
15. Bianchi, S., Davies, J. I., and Alton, P. B., *A&A*, **359**, 65 (2000).
16. Désert, F. X., Boulanger, F., and Puget, J. L., *A&A*, **237**, 215 (1990).
17. Bianchi, S., Davies, J. I., and Alton, P. B., *A&A*, **344**, L1 (1999).
18. Popescu, C. C., and Tuffs, R. J., *MNRAS*, **335**, L41 (2002).
19. Bianchi, S., *Modelling the FIR emission in spiral galaxies*, Ph.D. thesis, Cardiff University (1999).
20. Trewhella, M., *MNRAS*, **297**, 807 (1998).
21. Misiriotis, A., Papadakis, I. E., Kylafis, N. D., and Papamastorakis, J., *A&A*, **417**, 39 (2004).
22. Meijerink, R., Tilanus, R. P. J., Dullemond, C. P., Israel, F. P., and van der Werf, P. P., *A&A*, in press (2004).
23. Alton, P. B., Bianchi, S., and Davies, J., *Ap&SS*, **276**, 949 (2001).
24. Xilouris, E. M., Byun, Y. I., Kylafis, N. D., Paleologou, E. V., and Papamastorakis, J., *A&A*, **344**, 868 (1999).
25. Xilouris, E. M. 2004, in *The Spectral Energy Distribution of Gas-Rich Galaxies: Confronting Models with Data*, Heidelberg, 4-8 Oct. 2004, eds. C.C. Popescu and R.J. Tuffs, AIP Conf. Ser., in press
26. Popescu, C. C., Misiriotis, A., Kylafis, N. D., Tuffs, R. J., and Fischera, J., *A&A*, **362**, 138 (2000).
27. Popescu, C. C. 2004, in *The Spectral Energy Distribution of Gas-Rich Galaxies: Confronting Models with Data*, Heidelberg, 4-8 Oct. 2004, eds. C.C. Popescu and R.J. Tuffs, AIP Conf. Ser., in press
28. Misiriotis, A., Popescu, C. C., Tuffs, R., and Kylafis, N. D., *A&A*, **372**, 775 (2001).
29. Bianchi, S., Ferrara, A., Davies, J. I., and Alton, P. B., *MNRAS*, **311**, 601 (2000).
30. Misiriotis, A., and Bianchi, S., *A&A*, **384**, 866 (2002).
31. Kuchinski, L. E., Terndrup, D. M., Gordon, K. D., and Witt, A. N., *AJ*, **115**, 1438 (1998).
32. Alton, P. B., Xilouris, E. M., Bianchi, S., , Davies, J. I., and Kylafis, N., *A&A*, **356**, 795 (2000).
33. Alton, P. B., Xilouris, E. M., Misiriotis, A., Dasyra, K. M., and Dumke, M., *A&A*, **425**, 109 (2004).
34. Boulanger, F., Abergel, A., Bernard, J.-P., Burton, W., Désert, F.-X., Hartmann, D., Lagache, G., and Puget, J.-L., *A&A*, **312**, 256 (1996).
35. James, A., Dunne, L., Eales, S., and Edmunds, M. G., *MNRAS*, **335**, 753 (2002).
36. Kramer, C., Richer, J., Mookerjea, B., Alves, J., and Lada, C., *A&A*, **399**, 1073 (2003).

37. Bianchi, S., Gonçalves, J., Albrecht, M., Caselli, P., Chini, R., Galli, D., and Walmsley, M., *A&A*, **399**, L43 (2003).
38. Ossenkopf, V., and Henning, T., *A&A*, **291**, 943 (1994).